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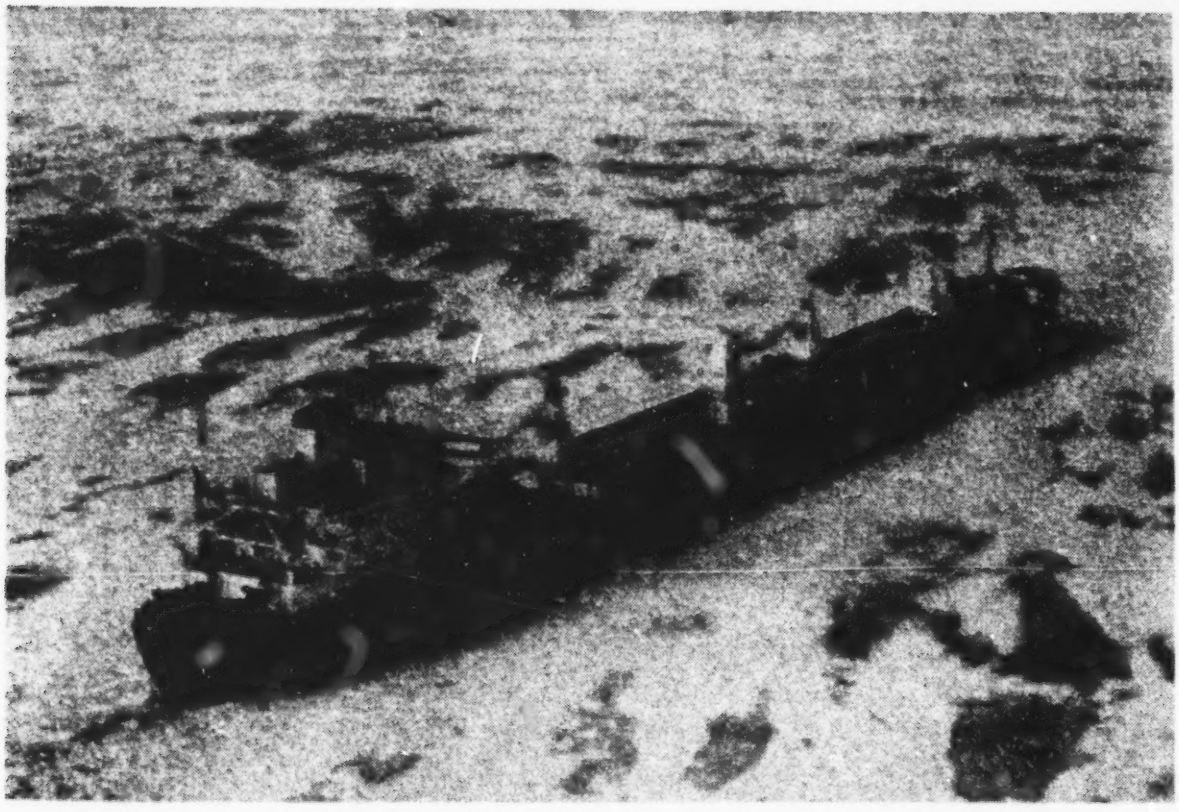
ERGONOMIC AND RESEARCH APPLICATIONS IN THE DEVELOPMENT OF AN ARCTIC SHIPHANDLING SIMULATOR

FINAL REPORT: VOLUME II



Prepared for
Transportation Development Centre
Transport Canada

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February 1985

TP 5623E

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Transport Canada / Transports Canada

David J. Ostry, Don C. Donderi, Oded J. Frenkel

MMS Man-Machine Systems Consultants Incorporated

Toronto, Ontario

February 1985

The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre.

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REPORT DOCUMENTATION FORM

1. Transport Canada Report No.	2. TDC Project No.	3. Recipient's Catalogue No.
TP 5623E	4935-4936	

4. Title and Subtitle	5. Report Date
Ergonomic and Research Applications in the Development of an Arctic Shiphandling Simulator Final Report Volume 11	February 1985
	6. Performing Organization Report No. MMS.84.02

7. Author(s)	8. Transport Canada File No.
D.J. Ostry, D.C. Donderi, O.J. Frenkel	D 1460-145-11-2

9. Performing Organization Name and Address	10. DSS File No.
MMS Man-Machine Systems Consultants Inc. P.O. Box 486, Station P Toronto, Ontario M5S 2S9	48SZ-T8200-2-2583
	11. DSS or Transport Canada Contract No. 1SZ82-00101

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Transportation Development Centre (TDC) 1000 Sherbrooke Street West, Suite 2421 Montreal, Quebec H3A 2R3	Final Report, 6/83 - 2/85
	14. Sponsoring Agency Code TDC 4935-4936

15. Supplementary Notes	16. TDC Project Officer
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17. Abstract

The major research priorities in Arctic navigation are identified and the human engineering aspects of these problems are considered in detail. The objectives are to specify research and training problems and to identify the techniques and instrumentation needed to obtain cost effective solutions. The appropriate techniques include classroom instruction, prototypes, mock-ups and laboratory studies as well as ice basin, fast-time and real-time simulation.

Research priorities are identified on the basis of an analysis of the literature, the task analysis results reported in Volume 1, and interviews with Canadian Coast Guard and industry personnel involved in Arctic navigation. Research and training needs as well as the appropriate methodology are specified in each of the major research areas. The report concludes with requirements for valid simulation of the Arctic environment and a discussion of techniques other than simulation which are applicable to work on ice-related marine technology.

18. Key Words	19. Distribution Statement
simulation, shiphandling, Arctic, ice cover, remote sensing, ship design, bridge design, bridge organization, ports, harbours	A limited number of copies are available from the sponsoring agency.

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price
unclassified	unclassified	47	NIL

FORMULE DE DOCUMENTATION POUR RAPPORT

1 N° du rapport Transports Canada	2 N° de l'étude — CDT	3 N° de catalogue du destinataire
TP 5623E	4935-4936	

4 Titre et sous-titre	5 Date du rapport
Ergonomic and Research Applications in the Development of an Arctic Shiphandling Simulator Final Report Volume II	février 1985
	6 N° du rapport de l'organisme exécutant MMS.84.02

7 Auteur(s)	8 N° de dossier Transports Canada
D.J. Ostry, D.C. Donderi, O.J. Frenkel	D 1460-145-11-2

9 Nom et adresse de l'organisme exécutant	10 N° de dossier — ASC
MMS Man-Machine Systems Consultants Inc., P.O. Box 486, Station P Toronto, Ontario M5S 2S9	48SZ-T8200-2-2583
	11 N° de contrat — ASC ou Transports Canada 1SZ82-00101

12 Nom et adresse de l'organisme parrain	13 Genre de rapport et période visée
Centre de développement des transports (CDT) 1000 ouest rue Sherbrooke, Suite 2421 Montréal, Québec H3A 2R3	Final 6/83 - 2/85
	14 Code de l'organisme parrain CDT 4935 - 4936

15 Remarques additionnelles	16 Agent de projet — CDT
	Ruth M. Heron

17 Résumé

Ce rapport définit les secteurs prioritaires de la recherche en matière de navigation maritime dans l'Arctique et étudie en profondeur les facteurs ergonomiques en jeu dans ce domaine. L'objectif fixé était de cerner les problèmes de recherche et de formation dans ce secteur, de même que les techniques et matériels d'essai nécessaires pour parvenir à des solutions rentables. Parmi les techniques retenues, mentionnons: la formation théorique, les expérimentations sur prototypes et maquettes et les études en laboratoire, ainsi que la simulation analogique en bassin et les techniques de simulation informatique en temps réel et en accéléré.

Les sujets de recherche prioritaires ont été définis après dépouillement de la documentation existante et à la lumière des analyses de fonctions présentées dans le tome 1 du rapport et des entrevues réalisées auprès de la Garde côtière canadienne et de l'industrie des transports maritimes dans l'Arctique. Le rapport détermine les besoins de recherche et de formation dans chacun des secteurs délimités, et propose un mode d'action précis à l'égard de chacun. Enfin, il précise les caractéristiques essentielles d'une simulation réaliste de l'environnement arctique avant d'aborder la question des techniques d'étude et de recherche glacielles ne faisant pas appel à une telle simulation.

18 Mots-clés	19 Diffusion
Simulation, manoeuvrabilité, Arctique, glaces, télédétection, architecture navale, passerelles de navigation, organisation du travail, ports	Le CDT dispose d'un nombre limité d'exemplaires.

20 Classification de sécurité (de ce rapport)	21 Classification de sécurité (de cette page)	22 Nombre de pages	23 Prix
non-classifié	non-classifiée	47	---

CDT TDC 79-005

Acknowledgements

The authors acknowledge the assistance of R. Heron and J. Nogrady of Transportation Development Centre, C. Stephenson, W. B. Wilson, W.B.J. Stewart, W.J. McCloy, I. Marr, W. Farish, J. Grinstead, and T. Irvine of the Canadian Coast Guard, Capt. D. Schofield, Capt. D. Deer, M. Luce and A. Sneyd of Canarctic Shipping, R. Lowry and J.B. Mercer of Intera Technologies, M.G. Lowings of Polar Sea Research, E. Rowan of Nanisivik Mines Ltd, R.W. Lumsden of Dome Petroleum, G. Harrison of Canadian Marine Drilling Company, J.G. Holburn of Melville Shipping, J. Carr of Carr and Donald and Associates, D.R. Miller of Arctec Canada, D. Lapp, D. Hagen, D. Wells of Norland Science and Engineering, W. McLean, J. Puglisi, A. D'Amico, J. Reik, J. O'Hara, and R. Feldman of the National Maritime Research Center, Kings Point, New York, and M. Carpenter of the Maritime Institute of Technology and Graduate Studies, Baltimore, Maryland.

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ERGONOMIC AND RESEARCH APPLICATIONS IN THE DEVELOPMENT OF AN ARCTIC SHIPHANDLING SIMULATOR

FINAL REPORT

VOLUME II

David J. Ostry, Don C. Donderi, Oded J. Frenkel

MMS Man-Machine Systems Consultants Incorporated

1. INTRODUCTION

Prior to the start of this project, the Transportation Development Centre (TDC) and the Canadian Coast Guard (CCG) conducted exploratory studies relevant to the development of an Arctic shiphandling simulator. The Coast Guard was primarily interested in a simulator for training purposes, since it would eliminate both the danger and the expense of conducting difficult manoeuvres at sea. Transportation Development Centre's interest was in research in ice navigation. The aim was the development of a year-round capability in the Arctic in order to support commercial resource development.

The early studies carried out by both departments focussed primarily on the development of mathematical formulations describing ship dynamics in ice. This project provides a complementary, equally necessary, ergonomic approach to simulator development. It specifies the optical fidelity and visual field requirements for simulation, given the perceptual limitations of the human operator and the nature of the navigator's decision making and other behaviour on the bridge.

The major goals of the study were to (a) determine the priority of research areas related to the safety and efficiency of ice navigation, (b) identify specific research questions within the most important of these areas, (c) establish the experimental designs necessary to deal with them and (d) specify the type of equipment needed for the research. The objective was to generate a framework for decision-making regarding the development, possibly on an evolving basis, of an ice-related simulator facility.

Since much of this information presented here has general application to simulator development, the interests of those who would use the device either for training or for research will be served.

1.1 General Strategy

The project was divided into three phases. Phase I was aimed at establishing priorities in research areas; phase II at establishing the necessary requirements for major research areas and the specification of the necessary simulation systems, and phase III at establishing the requirements for secondary research areas.

The work involved (1) an extensive literature review relating both to major research problems in Arctic navigation and to the design of simulation systems, (2) task analyses on the M.V. Arctic and (3) visits to major simulator sites. In addition, interviews were conducted with senior personnel in the Canadian Coast Guard and in commercial companies with interests in Arctic navigation.

1.2 Organization of the Report

This report consists of two volumes. There is, in addition, a summary report. The report was divided into two volumes to permit the technical findings (Volume I) and research and training needs (Volume II) to be dealt with separately.

In Volume I the literature relating to human factors in Arctic navigation is surveyed and the use of simulation for research and training is discussed. In addition, the findings of two bridge activity task analyses carried out on the M.V. Arctic in July and October 1983 are reported. Luminance levels and resolution requirements for simulation are presented and simulator motion is discussed.

In Volume II the major research priorities in Arctic navigation are identified and human engineering aspects of these areas are considered in detail. The objectives are to clarify research and training problems and to specify the techniques and instrumentation needed to obtain cost effective solutions. The sufficent conditions for successful simulator-based research and training are also discussed in Volume II.

In Section 2 of Volume II we identify research priorities based on an analysis of the literature, the task analysis results and interviews with Canadian Coast Guard and industry personnel involved in Arctic navigation. In Sections 3 through 7 we present recommendations regarding research and training needs in each of the major research areas. In Section 8 the methodology appropriate to each research area is described. In Section 9 we discuss the requirements for valid simulation of the Arctic environment. We also consider the other techniques applicable to work on ice related marine technology and we discuss the research and training that can be carried out with each.

2. RESEARCH PRIORITIES IN ARCTIC NAVIGATION TECHNOLOGY

In this section research priorities related to human engineering problems in Arctic navigation technology are identified. The identification and ordering of priorities is based on:

a) The literature on topics related to Arctic navigation technology (Volume I, Section 2),

b) The bridge activity task analyses conducted aboard the M.V. Arctic (Volume I, Sections 3 and 4), and

c) Rankings obtained from senior personnel in the Canadian Coast Guard and in Canadian corporations with commercial interests in Arctic navigation.

2.1 Numerical Rankings of Research Priorities

Ratings of research priorities in Arctic navigation technology were obtained during interviews with senior personnel from the Canadian Coast Guard, Dome Petroleum, Canadian Marine Drilling, Melville Shipping, Canarctic Shipping, and Arctec Canada (see Table 2.1).

The questionnaire was developed on the basis of the material presented in Volume I, site visits to the CAORF and MITAGS simulators, and information on the areas of active research interest at the University of Wales Institute of Science and Technology (McCallum, 1981) and at CAORF ("5 Year Research Plan, April, 1983", Unpublished document). The questionnaire was completed by ten people. Although the sample size was small, the raters were highly experienced and represent a wide range of Canadian Arctic interests. The ordering of priorities was consistent across raters and was consonant with our own evaluation based on task analyses and the research literature.

Respondents were asked to rank each of the items shown in Table 2.1 on a five point scale where a ranking of 1 indicated that research in a particular area was very important to improved Arctic navigation, and a rating of 5 indicated that work in this area was not at all important.

Table 2.1 Areas for Arctic Research

Research Area	Average Rating	Standard Error
Bridge Design	1.46	.24
displays and instrumentation	1.8	.58
equipment layout	1.4	.40
integrated bridge systems	1.2	.20
Bridge Procedures	1.58	.23
navigation planning	2.0	.63
watchstanding	1.4	.39
emergency response	1.4	.40
conning and piloting	1.7	.22
Ports and Waterways Design and Operation	2.84	.23
transit channels	3.2	.38
manoeuvring areas	3.0	.45
visual navigation aids (e.g., beacons)	2.0	.55
traffic management	3.3	.25
Navigational Aids and Remote Ice-Sensors	1.0	.00
Ship Design and Manoeuvrability	1.40	.22
piloted controllability	1.6	.40
inherent manoeuvring limits	1.2	.21

Table 2.1 gives the average rating and standard error for each of the evaluated items and the mean ratings and standard errors for each major category. In general, there was a higher overall ranking for the importance of research on navigational aids and sensors and a lower overall ranking for research on ports and harbours. Differences among rankings for research on ship design, bridge design, and bridge procedures were relatively small.

The items of highest priority were remote sensing, inherent manoeuvring limitations, bridge systems and layout, and watchkeeping and emergency response. These items concern navigation technology and human performance and error.

Kendall's coefficient of concordance (Siegel, 1956), a measure of inter-rater agreement was computed for the data set. The obtained value, $W = .54$, $p < .001$ indicates that there was significant agreement among raters on the research priorities for Arctic navigation.

3. REMOTE SENSING

The first operational radar was installed on the French transatlantic liner Normandie in 1931 -- to detect icebergs. The very first remote sensing technology was developed to help ships avoid ice. Until recently, however, few systems could provide ice information on a scale and at a rate adequate for tactical decision making in Arctic operations. Airborne systems now exist that can provide side-looking real-aperture radar (SLAR) or synthetic aperture radar (SAR) imagery either in real-time or near real-time to ships fitted with suitable receiving equipment. This remote sensing information is valuable in ice as has been demonstrated by its successful use on the M.V. Arctic in the eastern Arctic and by ships of the Canmar and BeauDril fleets in the Beaufort Sea.

We strongly recommend the continuing development of remote ice-sensing technologies. At present, SAR is the most promising by virtue of its coverage, resolution, and digital format, which provides the possibility of various image processing, pseudo-colouring and enhancement techniques as well as the potential for integration with other navigational aids. Other airborne imaging devices such as scatterometers or radiometers do not provide the coverage of the imaging radar systems. The development of specialized ship-mounted radars and appropriate display systems is also important for detecting leads and old sea ice and for detecting and tracking glacial ice.

In addition to the imaging capabilities of a remote sensing technology one must consider its cost, weight, reliability, and ease of maintenance, along with possibilities for its ship-board processing, enhancement and integration with other forms of ice information. In the following sections, we identify the research questions in three high priority sub-areas (see Table 3.1 for summary): 1) Remote Sensing Capabilities, 2) Image Processing and Display, 3) Display Coordination and Integration

3.1 General Research Strategy

Our approach is to evaluate remote sensing technology in terms of the capabilities and preferences of the human operator. Fitting the technology to the human operator both constrains remote sensing development decisions and requires ergonomic design of ship-board displays. Interestingly, few studies have focussed directly on operator performance with remote sensing displays. Exceptions are recent work by Lowry & Hengeveld (1980), Ford (1982) and Li & Bryan (1983).

Laboratory studies and field research will determine how information from remote sensing systems is to be displayed. The stimulus set (display materials) and behavioural measurement techniques are similar for all the proposed research. The studies require a reasonably large number of SAR displays in digital format of different ice conditions obtained at different incidence angles. The studies should focus on the 3 cm like-polarized SAR system that is

currently in wide use in the western Arctic. Both display preference and ice detection performance should be evaluated. Detectability performance should be assessed by using an unfamiliar stimulus set, preferably one for which ground truth is available (see Section 8, this volume, for research methodology).

3.2 Remote Sensing Capabilities

Information on ice-cover is obtained from ship-mounted and airborne microwave radars as well as visually. Satellite-mounted cameras or radars provide information on large scale characteristics of ice cover. They are important as aids to strategic planning. However, current commercial satellite imagery presently lacks the resolution required for an effective tactical aid.

The most promising tactical navigation aid is airborne SAR. Its imaging capability depends on the radar frequency, incidence angle, polarization, resolution and speckle, number of independent looks, and pixel size. Radar signatures also vary seasonally and with snow-cover (see Volume I; Hawkins, Gray, Livingstone & Arsenault, 1982; Lowry & Hengeveld, 1980; Onstott, Moore, Gogineni & Delker, 1982, for reviews).

The research strategy is to establish the spatial and grey/colour-scale resolution appropriate to the detection and identification of ice types by trained observers using systematically degraded SAR displays. We do not recommend that comparable studies be conducted for SLAR because development should be directed to the more powerful SAR technique. Likewise we do not recommend that human performance studies be carried out with radiometer or scatterometer information as these instruments are simply not rich enough information sources to be useful in Arctic navigation.

SAR research should be carried out on colour video displays that have as many bits per colour as possible. The choice of video displays over the currently more common photographic prints and transparencies is both in line with current developments in the remote sensing field and in addition, is the only realistic manner in which the information that is available to the operator can be maximized. Transparencies and photographic prints, with latitude and longitude added should be retained for Arctic operations in the near future. It is possible to study X-, C- and L-band imaging radars in both like polarized and cross polarized formats. We recommend that research focus on X-band like-polarized SAR because it is now currently in operation in the Canadian Arctic, it is a light weight, relatively inexpensive solution to the remote sensing problem and because, despite some controversy over the absolute superiority of like-polarized SAR for ice, it offers a very realistic optimization of radar parameters for ice detection.

The following questions should be answered:

(1) How many bits (grey or colour scales) are a) necessary and b) preferable to perform route planning and tactical navigation from SAR images?

(2) How are preference and performance affected by differences in spatial resolution of the SAR image?

(3) How does colour affect preference and performance? Speckle, for example, may be more distracting or noiselike in some or all colour mappings than in monochrome displays.

(4) What are the effects of changing the display size and scale?

(5) Do the patterns of preference and performance determined in (2) (3) and (4) vary with ice types and distributions?

(6) Is there an image resolution that is useable over the complete range of ice that will be encountered, although perhaps not optimal for all ice regimes?

(7) What are the operator requirements for ice detection and identification using ship-mounted radar? Do signal averaging or signal streaming improve detection performance or operator preference? Can false-colour be used to code old or glacial ice? How is ship-mounted radar best integrated with SAR?

In addition to questions related to microwave imaging radars there are a number of fundamental human performance questions related to the recognition of near-field objects. These studies should be run in parallel with the SAR studies described above:

(1) Conduct field studies to assess the effects of binoculars, filters, electronic image intensifiers (night vision aids), and search-light emission spectra on the visual acuity and operator preference in Arctic conditions.

3.3 Image Processing and Display

Image processing systems on ships operating in the Arctic must be affordable, durable, and sufficiently modular so that they can be maintained by relatively unsophisticated operators at sea. The estimated capital cost in 1984 for an array processor and colour display unit required to display SAR imagery is between $150,000 and $250,000.

In remote sensing "colour" implies the use of "false" colour or "pseudocolour": colour mapped onto an aspect of the remote sensing signal. The primary research question is what is the best mapping of colour onto signal variables.

Colour use may improve individual SAR displays, ship-mounted radar displays and integrated displays where one sensing system (e.g.,

SAR) is displayed as luminance and another (e.g., IR) is displayed as hue. It may be that SAR is better mapped onto a monochrome display and IR is better mapped onto colour or vice versa. Research should compare the relative advantages of mapping colour onto different imagery forms in preparation for computerized displays.

Another important question concerns operator control. It may be useful to have a rotating colour space in which hues for a particular intensity range are incrementally varied under operator control. Alternatively, colour scale steps or saturation may be changed by the operator to enable information extraction from low contrast areas. All of these techniques will make the display system more responsive to the operator and the condition of the received information but may also allow the operator to use the system at non-optimal settings. A false colour system for IR imagery that allows operator control of the colour scale steps is in use on the USCGC Polar Sea.

The following questions should be answered:

(1) What are the optimal colour mappings for SAR ice imagery? The answer requires mapping a wide range of spectrum characteristics onto grey scale levels and assessing preference and performance levels with each mapping.

(2) How many colour dimensions should be used (hue, saturation, brightness)? Our intuition is that saturation should be adjusted to an optimum level for hue but should not be used to index any signal property.

(3) How are performance and preference affected when the observer is allowed to establish colour mappings?

The answers must determine whether colour or operator control of colour enhance performance sufficiently to offset the increased cost.

3.4 Display Coordination and Integration

Information on ice cover is available from ship-mounted and airborne microwave radars, from facsimile ice maps and from visual observation. This information has to be used in conjunction with standard navigational charts and facsimile weather maps. The human engineering problem associated with these information sources is how should the information be presented in order to optimize operator peformance and minimize workload.

The work on display integration should focus on the coordination of SAR, ship-mounted radar, and facsimile ice maps. The possibility of incorporating a satellite down-link of IR and visible spectrum images for strategic planning should be considered.

A preliminary step is training in the use of facsimile ice maps. The system of ice classification that is currently used in Canada is sophisticated and complex. Although we feel that it is superior to that available in the U.S. for operations off Alaska, its

sophistication and complexity may have some disadvantages. On our Arctic task analysis voyages, some officers complained that the classification system is difficult to learn and remember. We assume that this is a problem of inadequate instruction. Since ice maps constitute a principal source of information for strategic passage planning, proper training must be provided.

An equally important problem is the coordination of SAR and ship-mounted radar displays. Since information from both kinds of radar is available on the bridge, their display parameters and presentation formats should be jointly optimized. We do not favour the actual integration of the SAR and ships' radar displays because the combination of visual information and visual noise in the resulting overlays would obscure important information in each of the displays. The strategy for this research is to systematically evaluate operator preference and ice detection performance by varying the size, scale, colour mapping and presentation format of simultaneously displayed SAR and ship-mounted radar images.

Table 3.1 Research Problems in Remote Ice-Sensing

Data Acquisition

General Problem:

Establish the resolution and display characteristics of SAR imagery appropriate to the detection and identification of different ice types.

Strategy:

Systematically degrade SAR displays obtained at different incidence angles. Evaluate preference and performance at each level of image degradation.

Specific Questions:

(1) How many bits (grey or colour scales) are a) necessary and b) preferable to navigate with SAR displays?

(2) How are preference and performance affected by differences in spatial resolution?

(3) How does the colour affect preference and performance?

(4) What are the effects on preference and performance of changing the display size and scale?

(5) Do the patterns of preference and performance determined in (2) (3) and (4) vary with ice types and distributions?

(6) Is there an image resolution that is useable for the complete range of ice that will be encountered, although perhaps not optimal for all given ice regimes?

(7) What are the operator requirements for ice detection and identification using ship-mounted radar? Do signal averaging or signal streaming improve detection performance or operator preference? Can false-colour be used to code old or glacial ice? How is ship-mounted radar best integrated with SAR?

Field Study Issues:

(1) Conduct field studies to assess the effects of binoculars, filters, electronic image intensifiers (night vision aids), and search-light emission spectra on the visual acuity in Arctic conditions.

Image Processing and Display

General Problem:

Establish the optimal colour enhancement procedures for SAR imagery.

Strategy:

Systematically evaluate operator preference and ice detection performance using false colour SAR displays.

Specific Questions:

(1) What are the optimal colour mappings for SAR ice imagery? Map a wide range of spectrum characteristics onto grey scale levels and assess preference and performance levels.

(2) How does colour affect image quality?

(3) How many colour dimensions should be used (hue, saturation, brightness) to code display information?

(4) How is performance and preference affected when the observer is allowed to establish colour mappings?

Display Coordination and Integration

General Problem:

Establish the optimal display coordination and integration procedures for the detection and identification of different ice types.

Strategy:

Systematically evaluate operator preference and ice detection performance by varying the size, scale, colour mapping and presentation format of simultaneously displayed SAR and ship-mounted radar images.

Specific Questions:

(1) Develop training techniques for the use of facsimile ice maps.

(2) Determine optimal size, scale, colour mapping and presentation format for simultaneously presented SAR and ships' radar displays.

---

4. MANOEUVRING STRATEGIES AND SHIP CONTROLLABILITY

There are few systematic descriptions of the intuitive knowledge that experienced arctic pilots possess or of their piloting behavior. Some "rule of thumb" information is available in Handbooks of the Canadian and American Coast Guards (Brigham, 1982; CCG, 1977). Manoeuvring strategies are also outlined by the Soviet ice-master Zubov.

The physical control of systems with exceedingly long time constants and substantial disturbance inputs is known to be difficult for the human operator (Kok and Stassen, 1980). Since operator error in the arctic may cause both financial and environmental losses, research and training in manoeuvring techniques is highly desirable. If an arctic ship simulator were developed, work on manoeuvring techniques would definitely constitute one of its principal applications (see, for example, "Study for a Canadian Shiphandling Simulator with Capability in the Ice Environment", Arctec Canada).

Operators could presumably benefit from real-time simulation without the accompanying operational risks. Simulation could be part of a comprehensive ice navigation training program. However, a far cheaper alternative can provide many of the same benefits: Classroom and textbook instruction on icebreaking strategies and techniques is a reasonable approach for teaching a variety of manoeuvring skills (Zubov's monograph, for example, has been used for training by the Canadian Coast Guard).

Since it is possible to convey many useful ideas about techniques and strategies for icebreaking by using low-cost classroom instruction supplemented by ship-board observation and training, the use of a simulator is justified only if can provide important experience more cheaply and safely than allowing the operator the actual control of the ship.

This additional experience requires realistic simulation of the ship-ice interaction. The development of skills to deal with a variety of ship-ice interactions is a major aspect of ship control that cannot be acquired through classroom instruction. However, if this experience is to be provided by a simulator it is essential that the equations of motion be adequate. If the model is inadequate, there is little to justify the development of a simulator. It is likewise clear that realistic models of the ship's motion in ice are a prerequisite for valid research.

The question of how accurate a dynamic simulation has to be is by no means a trivial one. However, it is well known that there are no principled means to derive equations of motion in multi-body systems (there is, for example, no analytic solution to the three-body problem). Accordingly, we recommend that if a simulator is to be developed, equations of motion should be derived, as they are in aircraft simulation, on the basis of system identification techniques using empirical time-series data gathered on ships' motion in ice.

5. BRIDGE DESIGN

5.1 Integrating Remote Sensing Information

The most important specifically Arctic problem in bridge design is how to combine the marine radar, visual observation and remote sensing data required to locate and navigate around ice hazards: thick first year ice, old ice, growlers, and icebergs. This is an important problem because all types of sensory information: visual, radar and remote sensing -- must be used within the same watch to plot, verify and then to correct a course through obstacles which may not be accurately detected, identified and located using any single one of the available sources of information. It is a bridge design problem because the components which provide the information: remote sensing controls and displays, radar controls and displays, and navigation controls and displays, must be positioned where they can be used in a mutually supportive way, and design decisions must be made about how much information should be displayed, as well as where and how it should be displayed.

An understanding of the importance of this problem was gained by first-hand observation of the use of downlinked side-looking airborne radar (SLAR) hard-copy imagery on the fall voyage of the M.V. Arctic. Summarizing comments about SLAR imagery recorded on October 25, 1983 between 1800 and 2000, we noted that:

> "...establishing position and scale is difficult. No navigation marks on imagery: this is an error and /marks/ should have appeared. No way of matching chart scale and SLAR scale. No way to work simultaneously with SLAR and nav chart because of scale incompatibility. /This is/ no problem if ship's position and navigation coordinates can be established on SLAR. Then it can be used as a plotting chart for manoeuvres. Inertial navigation system should supply this in form of grids on chart. At least one fixed point, scale and heading needed."

Our task analysis was carried out while the M.V. Arctic was equipped with a SLAR downlink. Radar technology has progressed to the point that synthetic aperture radar (SAR), which provides a better image than SLAR, is now available downlinked directly to a ship. Since SAR produces a better and more interpretable image than SLAR, it is the system of choice for future use.

The bridge design questions relevant to remote sensing concern the appropriate means of integrating the SLAR or SAR imagery into navigation activities. As suggested in the comments quoted above, the simplest, most useful and most conservative improvement would be to provide scale, orientation and navigational reference information on the hard-copy SLAR or SAR imagery. Then the SAR or SLAR imagery could be used directly to plot a course in the same way a navigation chart would be used, without requiring external references for position. This would immediately facilitate plotting and passage planning. Courses plotted on the SLAR or SAR image could then be transferred

manually to navigation charts with relatively little difficulty. Intera Technologies Ltd., which supplied the SLAR radar imagery to the M.V. Arctic, has incorporated all of these suggestions into the SAR and SLAR displays currently provided to the Beaufort Sea operations of Dome Petroleum and Gulf Canada Resources. These improvements solve the problem of orientation, but not the problem of ice interpretation on SAR or SLAR imagery.

Interpretation of SLAR or SAR imagery requires skill posessed by some ice experts but not by most Arctic captains. Improvements in SAR image and display resolution may improve interpretability of the image, and image-enhancement techniques like false-color representation of intensity may also improve interpretability. The usefulness of image enhancement remains to be demonstrated, and is an area for research proposed in the remote sensing section of this report.

It may also be possible to improve the usefulness of SAR imagery by updating its coordinates through reference to the shipboard marine radar display. By its very nature, SAR imagery pictures ice as it appeared some time in the past: perhaps as little as ten minutes, perhaps as much as two days ago. The shipboard marine radar display on the other hand pictures ice in the vicinity of the ship as it is at present. It may be possible to use the marine radar display in a systematic way to establish the present position of the ice patterns observed in the SAR imagery.

Observation of successive SAR and SLAR images shows that the large scale configuration of floes and leads often retains a patterned cohesion. As wind and current move the ice, the floes and leads translate and rotate across the water surface while maintaining their internal relationships which constitute the pattern.

The pattern of floes and leads which can be currently observed on the marine radar in the vicinity of the ship is thus potentially observable at some other position in the SAR image, because the ice pattern around the ship was at another position when the SAR image was recorded. Marine radar shows the observer the ice pattern in which the ship is currently centered; the SAR imagery tells the observer where that same pattern was at some earlier time.

It would be useful to be able to translate and rotate the SAR imagery ice pattern until it matches the ice pattern displayed on the marine radar. The result of this translation and rotation would be to reorient the entire ice configuration as observed on the SAR imagery at an earlier time to its current location based on the ice pattern currently visible on the marine radar display. It would also allow a calculation of ice drift based on the movement observed since the recording of the earlier SAR display. Knowledge of the present ice configuration and the ice drift are assets when navigating in ice.

There is no reason to anticipate a system in which an entire SAR image would be superimposed over an entire marine radar display. The resulting display would contain too much information and noise to be understood. Instead, we anticipate a system in which some of the SAR

imagery is transferred to the marine radar display, where it will be used to align identical features on the two displays simultaneously. The juxtaposition of the two sets of identical features will then be used to establish a new geogrpahical coordinate system for the entire SAR image. The geographically aligned SAR information can then be used to avoid ice hazards and to plot a course. The marine radar display is thus used to identify and to verify the position of the features identified in the SAR display.

A hard-copy remote sensing image is currently produced by the SLAR and SAR downlink systems. Advantages of a hard copy image are that a greater area can be displayed simultaneously at high resolution on a hard copy than on a visual display unit, and that the hard copy image -- with adequate reference information -- can be used as a plotting aid. The potential clearly exists for developing a digital storage and display system for SAR imagery which would eliminate the hard copy. Once the techniques for displaying digitized remote sensing imagery are perfected then the hard copy can be eliminated. In the short or medium term the hard copy image, with the addition of navigational reference information, should be retained for use directly as a plotting tool.

5.2 Visibility during Arctic Navigation

The second specifically Arctic problem in bridge design is to determine whether a high conning position is necessary. If it turns out to be necessary, the next step is then to determine the best location and instrumentation for it.

The communications and operations center of a merchant ship is the bridge. The main conning position is on or near the centerline, and near the chart table and communications equipment. It is already established that Arctic bridges need enclosed conning stations at the bridge wings in order to provide sheltered visibility and control while docking or manoeuvring in ice. It is also widely held (e.g., the Louis St. Laurent, the USCG Polar class icebreakers and the CCG Polar eight icebreaker design) that a high conning position should be included on an icebreaking vessel to insure adequate visibility forward of the bow.

Merchant ship crew sizes are small; considerations of safety as well as economy suggest that crew sizes can and should be further reduced (Herman, 1977, 1979; Riggs, 1979). How shall Arctic conning stations be designed to optimize ship handling with either one man (the officer of the watch), two men (the officer of the watch and helmsman) or three men (the officer of the watch, the helmsman, and the captain) on the bridge? Is it necessary (as in the USCG and CCG designs) to provide a two-man high conning position? Should the main console be designed cockpit-style to put all the essential controls in one position at the hands of the officer of the watch (Istace, 1977; Riggs, 1979)? How should the other controls be distributed? How many radar repeaters should be provided? It is possible to solve these bridge design problem by applying standard analytical techniques with reference to the task analysis data now available through this and

other current Arctic navigation research projects.

5.3 Glare Reduction

A third specifically Arctic bridge design problem concerns glare reduction. The need for effective glare reduction was observed during the two task analyses carried out aboard the M.V. Arctic. This problem is a small but important one. Polarized windows (as fitted in the M.V. Arctic) reduce glare, but they also reduce overall luminance by 18 percent, and consequently reduce contrast when it is most important, under conditions of low ambient illumination. Are there better solutions? One potential alternative is to mount tinted transparent roller shades on the inside of the bridge windows, which could be lowered when needed, and stowed "furled" when not needed.

5.4 Summary of Research Proposals

Experimental and analytic techniques have been developed for solving the bridge design problems described here. The techniques pertaining to remote sensing information are reviewed in Section 3. The techniques for evaluating a high conning position and for evaluating methods of glare reduction are described here in Table 5.1.

Table 5.1 Experimental and Analytical Techniques for Solving Problems in Arctic Bridge Design

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Evaluating a High Conning Position

1. Task analysis
   a) Specify tasks at each conning position
   b) Specify crew necessary to carry out tasks at each position
   c) Establish the performance benefits of a high conning position

2. Design decision
   a) Estimate the costs of a high conning position
   b) Make a cost-benefit analysis
   c) Decide whether or not to proceed with design

3. Design and test
   a) Design a high conning position based on task analysis
   b) Construct a small scale model
   c) Evaluate model by experienced Arctic officers using:
      i) structured interviews
      ii) questionnaires
   d) Revise model if necessary based on step c

4. Full-scale mockup
   a) Full-scale mockup constructed on basis of stage 3
   b) Evaluate mockup by experienced Arctic officers using:
      i) structured interviews
      ii) questionnaires
   c) Mockup revised if necessary based on step b

5. Construct a prototype and field test
   a)Method:
      i) structured interviews
      1) questionnaires

Glare Reduction

1. Obtain transparent tinted filter material

2. Produce tinted roller shades

3. Fit roller shades to a) polarized and b) unpolarized windows on an Arctic bridge

4. Field test of alternative configurations:
   a) sunglasses alone or with
   b) tinted roller shades, with or without
   c) polarized windows
      Methods:
      i) preference ratings
      ii) structured interviews
      iii) evaluation by target detection field experiments

6. SHIPBOARD ORGANIZATION AND COMMUNICATIONS

Very little of the research on shipboard organization and communication is specific to ice-breaking or to ship control in the Arctic. In the opinion of Arctic navigation experts we interviewed, the operational conditions in the Arctic are very different from those in lower latitudes. Thus, research and training specific to Arctic conditions has to be carried out separately from the research already available on shipboard organization and communication. Moreover, the existing research on shipboard organization and communication is incomplete and of variable quality.

As will become clear from the information presented below, a real-time simulator is the most appropriate tool for research on shipboard organization and communication in Arctic water. Our visits to the simulators now in operation have shown that none of the existing simulators have all of the necessary capabilities for carrying out research into operations in Arctic waters.

6.1 High Priority Areas of Research

Within the general area of Shipboard Organization and Communications the following areas of research are of particular importance to Arctic and/or icebreaking operations. The list is complete, in that while additional areas could be named they would be of only tertiary importance. We do not rank these areas according to importance. They are nearly equal in importance; and very little work which is specific to ship control in the Arctic has so far been done in any of these areas. Research is needed in all of them.

Urgency, based on the principle of "safety first" can guide the order in which the research should be carried out. We assign the highest priority to the areas which contribute most to safety, namely the areas A 3, 5, & 6; B 1, 2, & 3; D and F. The available research time of an Arctic ship simulator should first be devoted to these areas (see Table 6.1).

The complete list of the areas is as follows:

A. Shipboard organization and management

A. 1. Normal operations

A. 2. Difficult Circumstances and Maneouvres

A. 3. Emergencies

A. 4. Bridge and Shipboard Standard Procedures

A. 5. Transfer of Information Between Watches

A. 6. Team Training and Leadership Training

B. Communications

B. 1. Within Bridge

B. 2. Shipboard (within own ship)

B. 3. Between Different Ships

C. Workload and Stress

C. 1. Levels of Manning

2. Vigilance

3. Physical Stresses and Fatigue

4. Socio-psychological Stresses

D. Safety and Probabilistic Risk Analysis

E. The Selection, Design, and Evaluation of the Hardware and Software of Training Simulators

F. The Selection, Design, Evaluation and Validation of Various Team Training Methods and Scenarios

G. Determining the criteria for and the validity of certification procedures which use training simulator time instead of time at sea

Standard procedures (A 4) includes A 5, but the question of the transfer of information between watches is so important that we set A 5 as a separate heading.

It may appear that the Area B 3 is not specific to Arctic operations, and that it should be omitted from this list. However, a large proportion of losses in operations in ice are in fact collisions between ships (Brigham, 1982), rather than only rammings and groundings. Collisions occur in operations in ice because icebreakers are often called upon to aid other ships in difficult ice conditions, and this then involves operations in close proximity between the two ships. Another circumstance that calls for a high degree of cooperation between different ships is when two icebreakers work in tandem.

It is also well established from various American, Norwegian, and other studies (e.g., Paramore et al., 1978a, 1978b; Drager, 1980) that the single most important set of factors leading to collisions are failures of communications between bridges, and that these in turn are often related to failures of leadership and management within bridges. There are thus good reasons for inclusion of the communcations areas, particularly, area B 3 in our list.

"Safety" is not a separate area of research. Resolving the problems in several of the areas named here will also contribute to improving safety. However, probabilistic risk analyses, and the special role that a simulator would have in such analyses, require a separate heading.

A simulator which would be adequate to achieve objectives E, F, or G will have to be a full-task simulator which would provide the highest degrees of realism. This means that it would have a full range of capabilities to simulate all the factors and tasks which may need to be investigated, that is, which may affect the performance of ship operators or the quality of a training program.

On the other hand it is very often more economical to construct training simulators which have only a limited range of capabilities, restricted to the training missions to which they would be dedicated (e.g., tug operations in ice in a particular harbour). Thus, a full task research simulator can be used as the primary tool for the development and design of various training simulators, to determine the minimum functional, hardware, and software specifications needed for a particular type of training simulator. The research simulator can thus also be used to plan the purchase or construction of more economical training simulators.

6.2 Roles of Research Simulator in the Design of Training Simulators, Training Programs, and Certification Criteria

Among the high priority research areas in Shipboard Organization and Communication, issues related to the use of research simulators in the design of training simulators and training programs are of particular importance. There has been extensive work in this area on the cost/benefit structure of various simulator designs.

There is wide agreement among experts in simulation, and in particular among experts in marine simulation, about the following conclusions:

(1) A research simulator is an indispensable tool if one wishes to design cost-effective training simulators. For these purposes a research simulator ought to be the primary 'generative' device for developing, designing, and evaluating part-task and whole-task training simulators.

(2) A research simulator is not only a primary and essential tool for optimizing choices of hardware and software for training simulators — it is an essential tool for the development of comprehensive training programs for shiphandling. Comprehensive programs consist of a mix of time spent in classrooms, aboard ship, and on one or more part-task and whole-task training simulators. Development of a comprehensive program also involves specifying the optimal sequencing of these different training periods.

(3) Cost-benefit considerations leave little doubt that most training simulators need to have only a limited range of capabilities. These capabilities (e.g., own ship malfunctions) would be restricted to those needed for the aims to which the particular training simulator is dedicated. As a rule, this holds not only for part-task (e.g., radar operation) training simulators, but also for wheel-house simulators.

(4) On the other hand, to be most useful for the widest set of research missions and also to be capable of developing and testing training simulators and programs, a research simulator should have a wide range of capabilities. It is also desirable to be able to vary the capabilities and fidelity of the research simulator in order to simulate configurations which might be used as training simulators. Alternatively the research simulator should be designed in ways that allow for the addition and integration of further capabilities when these become needed and/or financially feasible. This was, for example, the rationale for the design of the CAORF research simulator of the U.S. National Maritime Research Center (at Kings Point, N.Y.). The experiences of the past decade in the applications of the CAORF simulator, including its uses for designing and evaluating training simulators and programs (Hammell et al. 1980; Hammell et al., 1981a, b), have demonstrated the validity of this rationale (Maclean, 1984; Puglisi, 1984).

These four conclusions are based on extensive experience in the aviation, space, and nuclear industries over the past thirty years (e.g., Roscoe, 1980; Lauber and Foushee, 1981; Hammell and Gardenier, 1980; and Hays and Singer, 1983). These conclusions emerge just as clearly from experience with the use of research and training simulators in the marine industry in more recent years (e.g., Hammell and Gardenier, 1980; Schuffel et al., 1981; Paffett, 1981; and Gardenier et al. 1983).

A sophisticated, and ergonomically sound, approach to the design and evaluation of simulator-based training is known as 'the systems approach to training'. It enables the identification of needed simulator characteristics on the basis of the detailed analysis of operator tasks. The U.S. Air Force and Navy, NASA, and certain commercial airlines have used it extensively, and several applications of it are well documented in the literature (Smode, Gruber, and Ely, 1963; Chenzoff and Folley, 1965; Gagne, 1966; Jeantheau, 1970; Cream, Eggmeier, and Klein, 1978; Hammell and Gardenier, 1980). The applicability and usefulness of this approach in the areas of marine training and certification has been recently demonstrated by two large studies (each of about three-man years), in which simulator-based training and certification of deck officers were evaluated (Hammell et al., 1980; Hammell et al., 1981a, b) for the U. S. Coast Guard and Maritime Administration.

The CAORF research simulator was a central tool in these two studies. More generally, a research simulator is an essential tool in

the systems approach to training. The systems approach to training can be used to estimate a cost-beneficial mix of time spent in classroom, on shipboard, and on a training-simulator, as well as an advantageous sequencing of these periods. More generally, it lends itself well to cost-benefit analyses of various hardware, software, scenario, and other components and options of a simulator based training program.

Extensive studies by the U.S. coast Guard and the U. S. Maritime Administration, and by similar bodies in other countries, have demonstrated the following conclusions (e.g., Hammell and Gardenier, 1980):

(1) On the basis of safety, cost, and control of training conditions, the simulator is preferable to on-the-job training at sea for most shiphandling skills.

(2) Ethical, safety, legal, or cost reasons dictate that skills called for by emergencies (e.g., disabled ship, near collision, or collision), and by difficult or hazardous environmental conditions, cannot be taught anywhere but on a simulator facility.

In recent years the advantages of training simulators for purposes of certification of mariners have also become recognized. It has been suggested internationally (IMCO Standards of Training and Watchkeeping Convention of 1978, Resolution 17), as well as legislated by some nations (e.g. the U.S. Tanker Safety Act of 1978), that simulators be used for demonstrating licence qualifications of mariners.

These conclusions have been demonstrated from research in shiphandling in non-Arctic waters. Turning to training and certification for shiphandling in Arctic waters -- the potentially more critical consequences of emergencies and losses, and the higher costs of operations in the Arctic, mean that these conclusions would hold a fortiori.

We make the following three recommendations :

I. Training and certification of deck officers for shiphandling in Arctic waters should consist of an appropriate sequence of time periods in classroom, on shipboard, and on part- and whole-task training simulators.

II. The 'systems approach to training', or an appropriate modificaton of it, should be used to develop simulator-based training and certification programs for shiphandling in Arctic waters. It would also allow cost-benefit comparisons of various training program options.

III. Particularly important applications of an Arctic research simulator would be its uses for the design and evaluation of training simulators, and of simulator-based training and

certification programs.

6.3 Need for a Research Simulator

A simulator dedicated to research into ship operations in the Arctic will be a highly useful, cost effective, and for certain areas of research an indispensable tool.

There are three possible environments for research on shipboard organization and communication: simulator, laboratory, and aboard ship. For each research problem the question arises: which environment or mix of environments is most suitable and effective? The question can be put more radically: can any of the research in these areas be carried out without the use of a simulator? Or perhaps with the use of only a very rudimentary simulator?

Each of the areas of research which we name above would need a simulator for at least some essential parts of the research. A simulator is the only environment which would allow research in the area of training in crew management in emergencies. There are many emergencies which would be too dangerous and/or too expensive to simulate aboard a ship at sea.

The cost of a full task simulator is of the same order of magnitude as that of a single large cargo ship. Taking only the contributions from the simulator research to increases in the safety of operations -- i.e. to reducing the frequency of various losses at sea -- would be more than sufficient to justify the costs of the facility as well as the costs of its continued operations.

Table 6.1 Shipboard Organization and Communications: High Priority Areas of Research

Sub-Area of Research	Technical Means
Emergencies	
1) simulation studies involving: event and link analyses determination of fault trees	high visual fidelity high realism (e.g., communications)
2) evaluation of crisis management techniques on simulator	high motion fidelity
Information Transfer between Watches	
1) Clarify requirements through interviews, task analyses, examination of existing regulations	interviews, task analyses
2) Validation of suggested procedures in static mock-up	static mockups
3) Validation of procedures in sea-trials	sea trials
Team Training and Leadership Training	
1) Evaluate allocation of tasks between masters and juniors	visual and motion fidelity - task dependent
2) Evaluate effectiveness of different training procedures (e.g., mix of individual and team training)	high fidelity communications
Communications	
1) Identify major communication failures (a) on bridge (b) shipboard (c) between ships and to shore stations	visual and motion fidelity - task dependent high fidelity communications off-bridge communications
2) Use simulator studies to refine the analysis of communication faults under controlled conditions	
3) Use results to suggest modifications to rules of the road, etc.	

7. PORTS AND HARBOURS

Shiphandling simulators have been used successfully in the design and siting of docking facilities in open water harbours (e.g., Atkins and Bertsch, 1979; Gress and French, 1980; Kaplan and Wentworth, 1980) and can play a comparable role in the Arctic.

At present, operator performance is taken into account in the site selection process by the use of static mockups: enlargements of navigational charts with mockups of ships and docking facilities superimposed. The suitability of a given configuration from the operator's point of view is determined by having experienced masters study the mockup and make suggestions. There is frequently considerable variation in the masters' evaluations. Consequently, it would be desirable to have an objective basis, such as a real-time simulator, on which to evaluate potential sites. This suggestion was supported in discussions with Canadian engineering firms involved in Arctic terminal design.

7.1 Human Engineering in Arctic Harbours

The docks and ore-terminals of the eastern Arctic (Nanisivik and Polaris) have been located as close as possible to the mine site. Since ship traffic has been relatively light and the facilities are situated in locations that did not require dredging, siting on the basis of proximity to shore-based operations has proved acceptable.

There are, however, some features of Arctic dock structures that are less acceptable to ships' masters. In particular, at both Nanisivik and Little Cornwallis Island, steel-sheet pile cells have been used to form the dock even though the circular structure can be dangerous to the ship while berthing (Figure 7.1). (The masters on the M.V. Arctic and M.S. Thuleland both expressed concern about the circular cells). Since a number of docking (and mooring) incidents and at least one grounding have occurred at these sites, the development of dock-approach strategies and additional shore-based docking aids would certainly be desirable.

A real-time simulator could be useful both for the development of approach techniques and for the evaluation of shore based docking aids. However, the validity of this work depends entirely on the existence of adequate models of the ship/ice interaction.

An important problem in docking is gauging the distance to the dock corner. J. Carr, of Carr and Donald and Associates, a Canadian engineering firm with extensive experience in Arctic terminal design, suggested that this problem might be alleviated by developing a special purpose microwave ranging system with shorebased reflectors that would be linked to a visual display which showed the position of the ship in relation to the dock. The hardware development of an appropriate ranging device is strictly an engineering concern. However, if the available information is to be useful to the operator the display characteristics may be particularly important. A real-

Figure 7.1 The jetty at Nanisivik viewed from the air

time simulator could prove helpful in this context.

In summary, there are a number of operator related problems in site selection and the design of facilities that could be aided by using a ship simulator. These are the evaluation of specific sites and docking facilities on the basis of objective evaluations of operator preference and performance. Included in this assessment could be evaluation of the the optimal number and spacing of sheet pile cells. This work requires suitable hydrodynamic models obtained from the actual harbour s tes as well as wind and current information. In addition, a simulator could be used to assist in the development of an operator display for a shipbased telemetry system for dock approach. This would permit optimization of the display from the point of view of operator performance.

8. RESEARCH METHODOLOGY

In this section the methodology appropriate to research and training in Arctic navigation technology is described. We have focused on those problems for which an adequate solution involves design decisions that take account of the preferences and abilities of the human operator. Some important problems in ice-related marine technology, such as, the inherent manoeuvring limitations of ships', do not have a significant human engineering component and as a result will not be considered.

We provide methodology for research in:

- remote ice sensing
- manoeuvring strategies and ship controllability
- bridge design
- bridge organization and communications
- ports and harbours

8.1 Remote Sensing

Laboratory studies should be conducted for SAR and ships' radar displays to identify the infomation to be presented and optimize the presentation format. The studies should focus, at least initially, on 3 cm radar systems. Both operator preference and ice detection performance should be evaluated.

8.1.1 Display Materials

A large number of SAR and ships' radar records of different ice conditions should be obtained in digital format from different incidence angles. The studies should be carried out under computer control on high resolution colour graphics displays. If possible, the SAR and ship's radar records should be obtained simultaneously. Ground truthing, at least relating to snow cover, ridge frequency, sail height and keel draft, should be obtained where possible.

8.1.2 Factors to be Examined

For both SAR and ships' radar displays the effects of following variables should be examined in order to determine the levels of each which optimize operator preference and ice identification performance:

- radar incidence angle
- ice cover variables

- thickness
- surface deformation
- surface water
- snow cover
- first year ice / old ice
- open water

- spatial resolution
- grey scale / colour scale resolution
- static colour mapping
- operator controlled colour steps
- rotating colour space
- display scale
- number of independent looks

8.1.3 Research Techniques

Although it is acceptable to present the same SAR image many times (with different resolution or enhancements) to an individual rater in order to obtain preference judgements, the ability to interpret the operator's ice detection performance rests on the availability of a relatively large stimulus set in which individual displays are presented only once. In detection studies, the problem with the repeated use of a small set of SAR images is that once an ice observer has identified the position of the old ice on one display, he is likely to identify it easily on subsequent re-presentations of the same display, even under different image enhancement conditions. Thus, little information is gained on differences in detectability among display conditions.

Two behavioral evaluation procedures should be used for the studies described below. The first is multidimensional scaling which provides a quantification of observer preference for displays. In this procedure, observers make judgments of both preference and similarity of image pairs on numerical scales. The technique enables the extraction of the number of factors used in the judgments and provides a correlation between these factors and the magnitudes of the physical variables used as the stimuli. Optimal levels for the variables that are identified should be determined by using Wald procedures (Taylor and Creelman, 1967; Wald, 1947). A second technique involves the use of signal detection measures of accuracy of identification (see Green and Swets, 1966). Here the ice observer's performance is evaluated. Depending on the size of the stimulus set,

either incomplete-factorial or full-factorial designs designs (possibly using Williams squares (Cochran and Cox, 1957) to balance first-order carry-over effects) should be used. Measures of both sensitivity and bias can be extracted as a function of the different independent manipulations.

8.2 Manoeuvring Strategies and Ship Controllability

Classroom instruction combined with shipboard training (or possibly combined with simulator training) should be provided. We wish to emphasize strongly that the validity of training or research on a real-time simulator related to manoeuvring techniques depends crucially on the development of adequate models of the ship-ice interaction.

8.2.1 Factors to be Examined

An extensive list of topics (and scenarios) appropriate to training in ice piloting is given in Arctec Canada's "Study for a Canadian Shiphandling Simulator with Capability in the Ice Environment". Manoeuvring techniques are also discussed in Brigham (1982). The topics covered in these works should form the basis of training scenarios for Arctic piloting.

8.2.2 Research Techniques

Simulator-based training and research related to manoeuvring techniques should not be carried out unless adequate models of ships' interaction with ice are available. However, on the assumption that a validation simulation can be developed, operator performance on the training scenarios cited above should be evaluated in terms of the following evaluation variables:

- informational adequacy and promptness of bridge communications
- informational adequacy and promptness of off-ship communications
- ships' speed in various ice conditions
- RMS deviation from track
- extreme deviation from track
- mean distance on backing before ramming in various ice conditions
- frequency of backing in various ice conditions

8.3 Bridge Design

Research on Arctic bridge design should be carried out by using field studies and full-scale bridge mockups. The mockups should be designed and evaluated by experienced Arctic captains, naval architects and human factors engineers.

8.3.1 Factors to be Examined

Field studies should be carried out to identify optimal search light characteristics and controls and to improve glare reduction techniques. The following variables should be assessed in terms of their effects on operator acuity (both with and without binoculars) and operator preference:

Searchlights:

- emission spectra
- overall luminance
- beam focus
- fixed vs. manoeuvrable searchlights
- auxiliary lights

Glare reduction:

- filter pass-band
- filter attenuation
- roller-shade vs. rigid filter design

Mockup studies should be carried out at the ship design stage. Visibility is paramount in all cases. Depending on the particular mission and manning of the ship the following factors should be considered:

- placement and design of control station
- integration of communications and command facilities
- integration of remote sensing displays into the navigating station
- design and evaluation of a high conning position

8.3.2 Research Techniques

For the field studies related to search light characteristics and glare reduction, operators' visual acuity and preference should be evaluated. Operators should provide detection responses plus confidence judgements and preference ratings for each stimulus. This will enable the calculation of measures of sensitivity and bias as the stimulus parameters are varied.

For mockup studies, the evaluation should be carried out by a team of human factors engineers, Arctic captains, and naval architects. The design priorities should be rank ordered on the basis of the ship's mission and manning and a number of possible layouts should be developed for evaluation. Mockups of the most promising alternatives should be constructed. The evaluators should cycle through the alternatives until agreement on the layout of the major functions is established. Particular attention should be given to the effect of various alternatives on the field of view. These techniques are already well established in bridge design (e.g., Anderson, 1977; Schuffel, 1977, 1978; Schuffel and Lazet, 1978; Schuffel, Truijens and Lazet, 1978; Schuffel, 1979).

8.4 Bridge Organization and Communications

Research and training related to bridge organization and communications in Arctic operations should be carried out in classrooms, ships, mockups and real-time simulators. The work should focus on the most urgent bridge organization problems:

- emergencies
- information transfer between watches
- team training and leadership training
- communications

8.4.1 Factors to be Examined

A number of factors should be examined in the areas listed above:

Manipulated Variables:

Training Variables

- number and function of officers on bridge
- individual vs. team training
- training in psychomotor skills vs. training in cognitive procedures

- varying the sequence and duration of periods in classroom, aboard ship, on part-task, and full-mission simulators

- debriefing feedback to trainees

Simulator Scenario Variables

- disabled ship, emergencies
  - changes to ship characteristics (e.g., rudder failure, partial or complete power failure, serious hull damage, listing to various degrees)
  - bridge malfunctions (e.g., failed or erroneous instrument indicators)
  - severity of emergency

- psychological and physical stresses
  - boredom, low arousal (e.g., emergency at end of boring watch)
  - fatigue (e.g., high workload, stresses during watch)
  - noise and vibration levels on bridge
  - roll and pitch on bridge

- difficulty of decision making
  - introduction of distractions
  - normal vs. additional vs. excessive workload
  - anticipated vs. unanticipated difficulties
  - simple vs. complex manoeuvring sequences

Watch-Change Variables

- time overlap between watches

- number of officers on watch

- standardized vs. non-standardized procedure

- availability of notes and other aids for pertinent information

Measurement Variables:

Information Transfer Errors

- errors classified by message type (e.g., observation, request, command, warning, acknowledgement)

- errors classified by message origin (e.g., master, ice-observer)

- errors classified by message media (e.g., radio, interphone, voice, navigation instruments)

- message failure (e.g., message not originated, message incomplete or ambiguous, message correct but untimely, message not received)

- number of errors, frequency per unit time and severity of consequences

Team Functioning

- time spent in preparing transits

- number, clarity of master's expectations regarding performance

- extent of delegation by Master or OOD of tasks to others

- origin, type, medium, quality (accuracy and use of standardized language), and failures of information transmitted (see list above)

- measures of cross-checks, corrections of others (e.g., by master of subordinates, by subordinates of master, number of persistent corrections of master by subordinates)

- number of detected errors (by master, by subordinates)

- number of errors knowingly not corrected by senior officer, by subordinates

- extent of usage of information sources available (during planning, during execution)

- latency to detect failures / error

- time reserves available to master to consult, plan, or take breaks

- time spent in briefing the relieving watch

Functioning in Emergencies

- number of alternate procedures considered

- number of officers delegated to alternate procedures

- number, quality of monitoring of viable procedures by master

- number of procedures discontinued by master

- number of diversions to non-essential tasks by master, by subordinates

- final success/failure rates

Validation at Sea

- long-term follow-up statistics of casualties by different groups (e.g., team trained vs. non-team trained)

- short-term follow-up: all appropriate performance measures listed above which can be taken on bridges during ship operation

8.5 Ports and Harbours

Operator evaluation of dock placement and design and studies related to dock approach should be carried out by using a ship simulator. The validity of these studies depends crucially on the availability of adequate models of ship-ice interaction.

8.5.1 Factors to be Examined

The evaluation of potential dock sites and docking facilities in terms of operator performance and preference provides an objective test on which design decisions can be based. At a potential dock site differences in operator performance (and preference) should be evaluated as a function of:

- the number and spacing of sheet pile cells

- alternative dock structures (e.g., rock-filled timber crib)

- orientation of the dock-face relative to the dominant winds and currents

- presence of ice in the berthing area

- presence of ice on the quay walls

- shore-based ranging aids

8.5.2 Research Techniques

Simulation studies to aid in Arctic site selection and the design of the docking facility should only be carried out to evaluate highly promising design alternatives. The following variables should be measured:

- informational adequacy and promptness of bridge communications

- informational adequacy and promptness of off-ship communications

- ships' speed approaching dock in various ice conditions

- number of attempts at docking

- RMS deviation from track

- extreme deviation from track

Standard experimental designs should not be used. By allowing the instructor the ability to alter the presentation order as necessary, the amount of information available using this procedure is maximized.

9. SIMULATOR CRITERIA

This section reviews the constraints placed on simulator design by the need to simulate accurately different aspects of the Arctic environment for different research and training purposes. It is arranged in increasing order of simulator fidelity, and consequently in increasing order of simulator flexibility. The section ends with a review of the material requirements for Arctic navigation research and training which do not require a simulator, but which can be realized using static mockups, video display terminals, cinema or photographs.

The precondition for development of an Arctic shiphandling simulator is an adequate dynamic model of ship-ice interaction. No matter how faithfully a simulator may reproduce the visual environment or ship motion, it will give false research data and produce useless training unless the simulator adequately represents the motion relationship between ship and environment.

The main variables of simulator design from the ergonomics point of view are the extent of the simulated visual field, the method of presenting the visual scene and the type of physical motion which is included in the simulator.

As indicated in Section 5 of Volume I, we recommend the adoption of computer-generated imagery as the visual image generation technique for an Arctic shiphandling simulator. Video disk storage techniques may be suitable to increase the memory capacity required for the more extensive visual field which will be needed to simulate many Arctic scenarios.

9.1 Vision Astern

Our data reported in Section 4 of Volume I demonstrate that astern manoeuvres are frequent in ramming and docking, and that the aft wheelhouse windows are used frequently during both ahead and astern manoeuvres in ice. We observe (Figure 9.1) that the wake of the M.V. Arctic viewed at a visual angle of 14 degrees from horizontal and seen at a slant range of 63 meters subtends a horizontal visual extent 26 degrees. The same wake viewed at an angle of 40 degrees from horizontal and seen at a slant range of 30 meters (about 26 meters from the ship) has a horizontal visual extent of 48 degrees. The wake at this visual angle can be seen from the aft bridge windows located at the beam ends of the bridge.

We therefore recommend that the minimum visual field for an Arctic navigation simulator include an astern segment of at least 48 degrees horizontal visual angle. As a matter of comparison with existing visual simulation capabilities, the MITAGS simulator has 360 degrees horizontal visibility with a computer-controlled projected light display. The IHI simulator in Tokyo has a 100 degree forward horizontal visual field with computer-controlled film and rear projected slide displays. The simulators in Kings Point and Bremen which use computer generated imagery have forward visual fields of 240

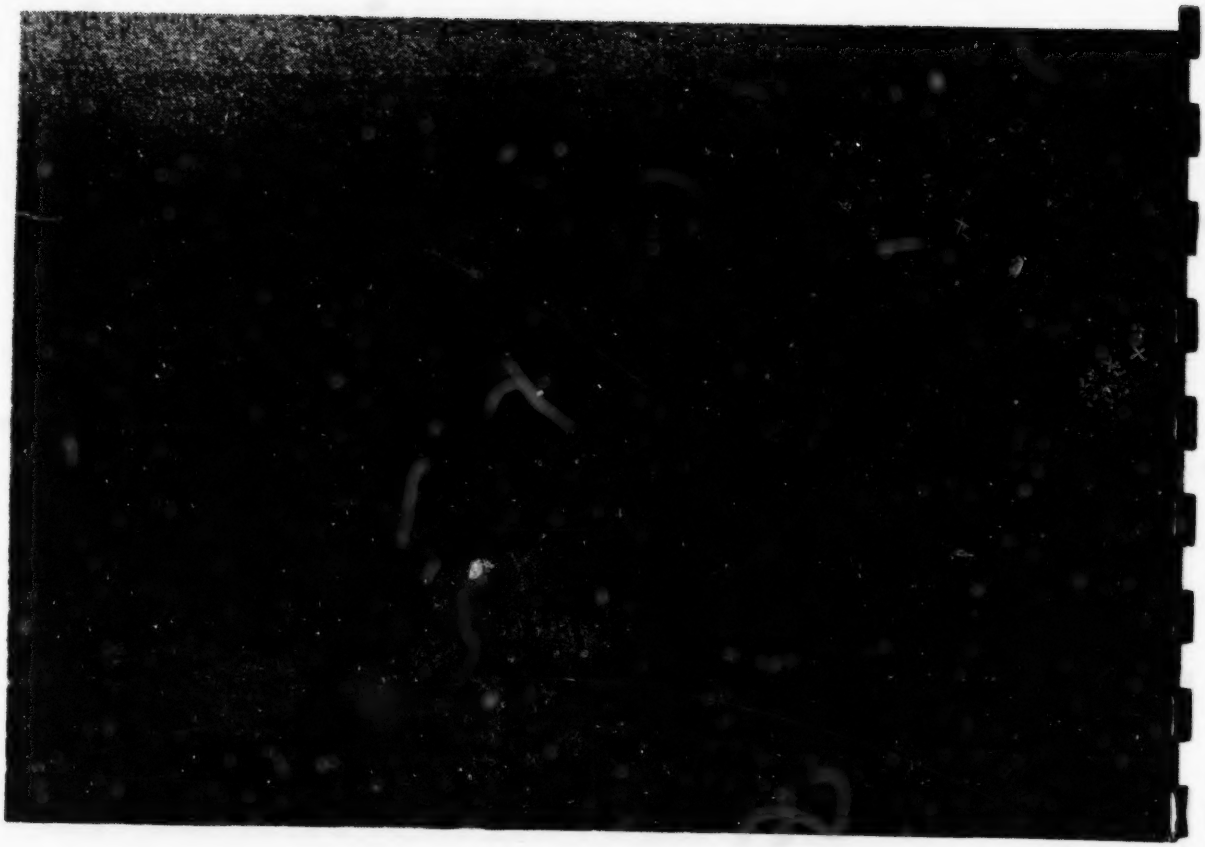

Figure 9.1 Wake of M.V. Arctic observed from aft bridge windows

and 250 degrees horizontal visual extent, respectively. An astern component of the visual field is not available in the present generation of simulators.

9.2 Vision Forward

We also recommend that the practice established with computer-generated imagery simulators of including a forward visual field of 120 degrees to both sides of the forward midline be maintained for an Arctic shiphandling simultor. A wide field takes advantage of the high sensitivity of the peripheral visual system to motion cues transmitted through the visual flow pattern of ice features past the simulated wheelhouse. Slow transit and turning motions can be effectively simulated through visual cues alone in an environment which contains peripheral visual flow patterns like those of the ice surface.

9.3 Vision Alongside

The extent of the vertical field of view of simulators is limited by the complexities of projection onto a non-cylindrical surface, although these complexities have been confronted in aviation combat simulators where an extensive field of view in all directions is essential. None of the shiphandling simulators uses a spherical or angled projection screen, and so the extent of their vertical coverage below the horizon is limited by the intersection of the projection screen with the simulator room floor. The vertical extent of simulation is usually between ten to twenty degrees above the horizon, to about twenty degrees below the horizon. With a simulated wheelhouse height of 15 meters, this brings the lower limit of simulation to within about forty meters of the simulated ship's side.

Task analysis data of masters' window use and visual observations in heavy first year ice show that observations directly alongside, and views both forward and aft from directly alongside at the water level are frequent while docking and ramming: manoeuvres which require an assessment of the ice thickness and distribution alongside and astern.

If the shiphandling simulator is to be used for scenarios requiring docking and backing during ramming, we recommend lateral visual simulation to seventy degrees below the horizon. Given a simulated wheelhouse height of fifteen meters, this brings the simulated sea or ice surface to about six meters from the ship's side. A ship moving with a lateral velocity of one knot is moving at 0.51 meters per second. The six-meter simulation limit means that a lateral ice or surface feature moving directly toward the ship will hit it in about twelve seconds from the time it disappears below the limit of visual simulation. The engine and helm response of a massive ship moving at slow speeds is not appreciably faster than twelve seconds; consequently any command based on the presence of a surface feature would have to be given before the feature reached the lower edge of the screen for the command to be effective.

A visual simulation limited to twenty degrees below the horizon has an associated minimum simulated range of 40 meters from the ship's side. A surface feature moving laterally towards the ship at this forty meter lower limit of visual simulation with a velocity of one knot would hit the ship in about eighty seconds. This interval of time without visual feedback is too long to give a realistic simulation of the effects of control actions taken in response to nearby ice features, and the distance from the ship is so great that potentially effective control responses to features closer to the ship than forty meters cannot be simulated. Therefore the 20 degree vertical simulation below the horizon which is now standard for computer-generated imagery simulators is inadequate for simulating docking or backing in thick ice, where visual observation of ice features adjacent to the ship is a common component of the behavior of masters.

9.4 Motion

A salient fact of Arctic navigation which influences both simulated and real shiphandling is that ice is an irregular medium which imparts irregular or random motions to a ship. Some of these motions are experienced as vibration, especially when ice is being milled by the propellors. Motions are also experienced as jerks (abrupt changes of acceleration) on the x, y and z axes. The motions also change velocity and acceleration in all three axes of rotation, and add roll, pitch and yaw to the normal motions of a ship.

There is no experimental evidence which demands the inclusion of vibration or motion in an Arctic shiphandling simulator. On the other hand, there is no conclusive experimental evidence that justifies its exclusion.

On the basis of our analysis in Volume I, we conclude that the realism and user acceptability of an Arctic shiphandling simulator will be significantly increased by the inclusion of vibration and noise as minimum acoustic and motion stimuli. In the absence of conclusive experimental data, this is our recommended minimum fidelity for motion in an Arctic shiphandling simulator.

To summarize our argument so far, the minimum ergonomic requirement for an Arctic shiphandling simulator includes the following capabilities: simulation of vibration and noise, horizontal visual field of 120 degrees to both sides of the forward midline and 24 degrees to both sides of the midline astern, vertical visual field of twenty degrees below the horizon, and standard computer graphics video capabilities with respect to resolution and color range. Given an adequate ship-ice interaction model, these visual field and motion capabilities will permit the simulation of navigation in level first year ice under all conditions except manoeuvring around low ice or land surface features as in docking, and backing and ramming in thicker ice.

9.5 Additional Simulator Capabilities

A simulator capable of presenting an environment of thick first year or old ice for research or training involving ramming, backing and docking would require all of visual field capabilities described above, plus simulation of the sea surface to within about six meters of the ship. This means a vertical extent of visual simulation to seventy degrees below the horizon.

Visual resolution problems will not occur when surfaces as close as six meters to the ship are simulated. While it has already been established in Section 5 of Volume I that standard video projection systems provide less resolution than the human visual system, it is also clear from the analysis of the visual details of Arctic scenes that the features of interest in simulating the Arctic environment are much larger than the minimally resolvable details of human vision. This is as true close to the ship as it is further away. Large ice blocks and ice edges are significant features. Ice pieces which approach the limit of human resolution or which are small enough so that their numbers would tax the vertex or edge-generating capabilities of the display system are not significant details and could be ignored or represented with less than full detail. The provision of video disk storage for visual details which can be presented in a non-interactive fashion is suggested as a means of increasing the storage and display capacity of a CGI system to cover the wider recommended visual field.

Thick first year or old ice also imposes larger accelerations and impulses on a ship in all three motion axes. Research data are not available to determine how much of an improvement in acceptability would occur by improving physical motion simulation. An addition consistent with our analysis of motion in the Arctic environment would be the capacity to generate roll, pitch and heave: rotations around the x and y axes, and translations along the z axis. A simulator with this capability could also provide research and training scenarios involving navigation in the open sea with significant wind and wave forces. The MITAGS simulator in Baltimore has this capability. The relevant Arctic scenarios involve navigating at the ice edge or in the bergy water of Davis Strait or Baffin Bay. This additional motion capability would also improve the acceptability of scenarios in thick first year or old ice, because the motion consequences of encounters with individual ice pieces could be better simulated. As indicated earlier, however, there is no data on how much better the acceptability would be with this additional motion.

No additional simulator capabilities are needed to adequately simulate the Arctic marine environment. Additional improvements will increase the acceptability of the simulator, but the capabilities described in the preceding paragraphs are sufficient to provide the Arctic scenarios described in the preceding paragraphs. Table 9.1 summarizes the simulation research and training scenarios and the simulator capabilities required to produce each of them.

9.6 Other Research Techniques

Some research and training scenarios do not require that the interaction of a ship with the Arctic environment be modeled with the exactitude of a shiphandling simulator.. We have earlier identified research and training on the integration and use of remote sensing information and research on bridge design as problems which do not require full simulation.

Research on the design and layout of bridge instrumentation and controls can be carried out in the laboratory and with static mockups. Analysis and laboratory testing of new instrument or control configurations normally precedes their incorporation into first a small-scale, and then a full-scale model of their intended location. Research techniques for evaluating preference and performance on bridge instruments and layouts are discussed in an earlier section.

Remote sensing information presents research problems of display integration: how shall two or more displays (e.g., marine radar, SAR, forward scanning sonar) be used and displayed together, and of control and display design: what display options should be available to the operator, and what characteristics of the information display (e.g., resolution and color) should be provided. The minimum requirement for laboratory research on these problems is the availablility of display images to study; these can be stored and reproduced from earlier missions on which the images were collected. Laboratory research using standard techniques for evaluating performance and preference can proceed with the image controls and displays alone; later on the results of this research can be incorporated into static mockups or simulators when the remote sensors are integrated into an overall bridge design.

9.7 Hardware and Software Options and Associated Costs

In aircraft simulation it is possible to precisely tailor a simulator to the user's needs. In ship simulation, the range of hardware options is more restricted. The ship simulator industry is not large enough for vendors to be able to offer their customers a wide selection of visual, hydraulic and computer systems. Software options are similarly restricted. Vendors have preferred computers for their simulators and have gained expertise in certain programming languages. It is necessary to approach the development of a ship simulator appreciating these constraints.

In addition, the development of an accurate cost estimate for a shiphandling simulator is a task of several person-months duration and itself a costly exercise for the potential vendor. Therefore detailed and binding cost estimates will not be available until serious negotiations for the purchase of a shiphandling simulator have begun.

Table 9.1 Ergonomics Criteria for Vision and Motion in an Arctic Shiphandling Simulator

Criteria	Scenarios
Image Generation: Computer-generated imagery (CGI)	
Visual image resolution: current CGI state-of-the-art	
Scene Luminance: 16 ft.-lambert maximum, details as developed in I.5.3	Manoeuvring in first year ice
Horizontal visual field forward: 120 degrees to both sides of midline (240 degrees in total)	
Horizontal visual field astern: 24 degrees to both sides of the midline (48 degrees in total)	
Vertical field above horizon: 10 degrees	
Vertical field below horizon: 20 degrees	
Motion: vibration	
	Manoeuvring in thick first year ice or old ice
Add motion: roll, pitch and heave and add vertical field below horizon: 70 degrees, to all of the above	Backing and ramming
	Close quarters manoeuvring
	Docking
	Emergency procedures

Note - see I.5 and II.5 for reviews of simulator design criteria

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